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13. ABSTRACT *(Maximum 200 words)*
The guidelines for assessing worker's level of heat strain in order to prevent thermal injury and performance impairment has been widely adapted in industries to promote workers' health and safety. Core temperature (Tcore) is a common physiological parameter used in the guidelines for heat stress; however, measuring Tcore may be invasive and impractical for real time monitoring a worker's health status. This study is a preliminary investigation of non-invasive warning indicator, Red Zone (RZ), for heat strain derived from the combination of heart rate (HR) and skin temperature (Tskin). Individual data from five datasets (Age = 22 ± 5 yrs, BMI = 23.0 ± 2.6, N = 43) were utilized to establish the RZ system. Analysis of the termination points relative to Tskin and HR were identified, along with Body Mass Index for individual differences. The data classified by RZ system were compared to their individual Tcore, using Fisher's exact test. Overall, the data points classified by the RZ system showed relatively good agreement (60-80% probability) with Tcore ($p < 0.05$). The RZ is a reasonable approach to warn occupational workers that they are approaching or/under thermal strain.

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Noninvasive warning indicator of the "Red Zone" of potential thermal injury and performance impairment: A pilot study.

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INTRODUCTION

Guidelines for assessing workers' level of heat strain to prevent thermal injury and performance impairment have been widely adopted by private industries to promote workers' health and safety. Internal body temperature (T_{core}) is the common physiological parameter for heat strain assessment as it reliably indicates impending injury (1,2). Laboratory studies as well as occupational guidelines for civilian workforces (e.g., metal and glass workers, fire fighters) and military personnel, all suggest regulating workers' operational or environment conditions when T_{core} is 38.0°C (100.4°F) - 38.5°C (101.3°F) (1,2,3). However, measuring T_{core} may be invasive and impractical for real time monitoring of worker's health status or Soldiers engaged in long hours of various multiple and unpredictable tasks in hot environments.

Skin temperature (T_{skin}) and heart rate (HR) are non-invasive, easily measured physiological parameters that are also indicators of the thermo-vascular status of workers exposed to thermal stress. Skin blood flows and sweating are active primary control mechanisms for T_{core} (4). If the T_{core} rises above its set point (~37°C), blood flow to the skin increases. Normal blood flow to the skin for a comfortable sedentary person is about 6 $L{\bullet}h^{-1}{\bullet}m^{-2}$ but can increase to 90 $L{\bullet}h^{-1}{\bullet}m^{-2}$ or higher, when a person becomes overheated (4). T_{skin} rises as a result of the warm blood flow to the skin. Under the conditions of excessive body heat, T_{skin} approaches T_{core}, and thermoregulatory insufficiency may occur due to the minimal heat transfer.

HR increases as oxygen consumption increases during work (4). The worker's sustained HR should not exceed a value of 180 – age, or the limit of maximal HR (HR_{max}) at the workplace should not exceed the 185 – 0.65*age (3). Despite the documentation that these physiological non-invasive measures increase with T_{core} under excessive heat exposure (4,5), the combination of HR and skin temperature are rarely utilized for occupational performance advisories or guidance.

This paper presents a preliminary investigation of the impeding heat strain warning system called Red Zone (RZ), which is based on non-invasive measures of HR and T_{skin} combined with Body Mass Index (BMI). Individual differences characterized by BMI relate to differences in physiological responses to heat exposure (6,7) and improve the accuracy of the RZ warning system for individuals.

MATERIALS AND METHODS

Individual data from four USARIEM datasets (Age = 25 ± 6 yrs, BMI = 23.9 ± 3.1, N = 19) and a heat tolerance study (Age = 19 ± 1yrs, BMI = 24.5 ± 3.2, N = 24) were used to formulate the Red Zone. Table 1 depicts the summary of five study conditions. Thigh or chest skin temperatures were examined in these data because they were less variable than T_{skin} taken from arm or calf regions.

Because T_{skin} for USARIEM study4 were not monitored, T_{skin} of these subjects were estimated by SCENARIO, a USARIEM thermoregulatory mathematical model (8). In all studies, subjects discontinued a test when T_{core} reached 39.5°C. In addition, testing was stopped when subjects reached 95% of age-estimated HR_{max} or remained at 90-94% of age-estimated HR_{max} for 5 minutes.

Table 1. Summary of five study conditions used in this study.

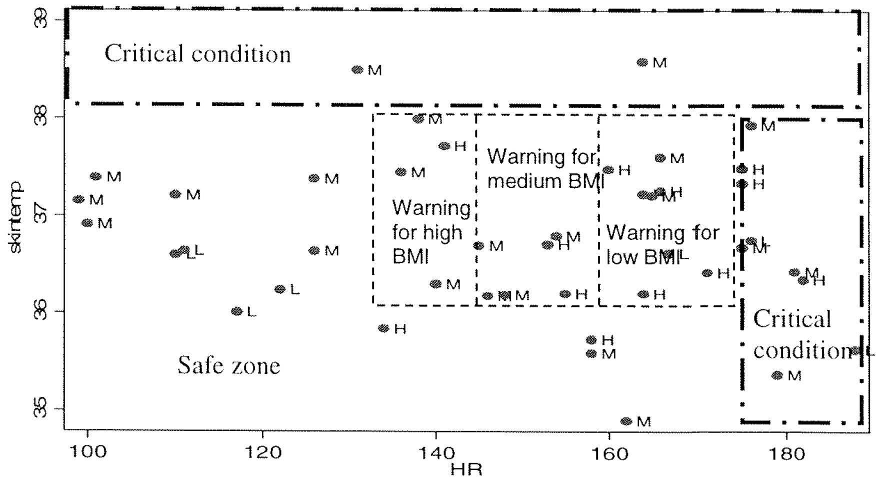
Database (reference)	N	Lab vs Field	Weather (mean)	Main activity	Clothing	Duration
USARIEM study1 (9)	5	Lab	38°C, 30%RH	walk (2 mph, 0% grade)	CP	240 min
USARIEM study2 (10)	5	Lab	30°C, 30%RH	walk (1.46 ms^{-1}, 2% grade)	CP	80 min
USARIEM study3 (11)	7	Lab	30°C, 38%RH	walk (3 mph, 2% grade)	CP	45-90 min
USARIEM study4*	2	Field	34°C, 44%RH	walk (altitude up to 350m)	BDU	all day
Heat tolerance study (5)	24	Lab	40°C, 40%RH	walk (5 $km.h^{-1}$, 2% grade)	Shorts, T-shirt	120 min

Database: * indicates an unpublished study
Clothing: CP = Chemical Protective Garment; BDU = Battle Dress Uniform

The final measurements of T_{skin} and HR for all tests and BMI were compared. BMI is relatively convenient to measure and is beneficial to describe associations with body fat, age, and gender. BMI, calculated by (weight, kg)/(height^2, m^2), was the only consistently measured individual parameter available between the datasets. When a BMI was unavailable (Heat tolerance study), it was randomly generated for the individual subject from the mean and standard deviation of published BMI data. Subjects were categorized into three BMI groups: a) low <= 20; b) 20 <medium <25; c) high >= 25. The RZ was also classified into three conditions: a) good/safe; b) experiencing heat/warning; and c) critical/overheated. The individual subject data labeled with these Red Zone categories based on their physiological responses were compared to their individual T_{core}, using Fisher's exact test.

RESULTS

The termination points for combinations of T_{skin} and HR from the 5 different studies are summarized by BMI, shown in Figure 1. T_{skin} above 38°C is likely to indicate potential heat injury irrespective of HR (upper area in Figure 1). When T_{skin} and HR simultaneously occur above respective thresholds of 36°C and the subject's HR warning threshold, there is an increasing probability of impeding hyperthermia, heat injury and performance decrements. When T_{skin} ranges between 36°C and 38°C, the HR warning threshold is BMI dependent and increases as BMI is lower (three dotted BMI boxes in Figure 1). When an individual's BMI is high (>= 25), he/she is likely to experience hyperthermia and heat stress at a lower HR than medium/light BMI individuals. Low BMI individuals (<= 20) are less likely to experience potential heat injury until HR limits reach to around 160-175 bpm (Figure 1).



— · · indicates critical/warning conditions
------- indicates warning conditions for addressed BMI.
BMI: L = low; M = medium; H = high

Figure 1. Red Zone model based on heart rate (HR, bpm), skin temperature (T_{skin}, °C) and three BMI categories (low, medium, high) applied for 5 studies.

Table 2 demonstrates the relationships of termination points between T_{core} classified by a standard heat guidelines (T_{core} = 38.5°C as a threshold) (1,2) and T_{skin} categorized by the RZ model. The accuracy in the RZ warning that T_{core} is greater than 38.5 °C is around 60%. Similarly, T_{core} below 38.5°C was classified as no warning in RZ with ~60% accuracy. False positive rate (T_{skin} was classified as a safe condition, although T_{core} was recorded above 38.5°C) was around 20%. The data points classified by the three RZ categories showed relatively good agreement with T_{core} (Fisher's exact, $p < 0.05$).

Table 2. The assessment of relationship between categorical Red Zone classifications and core temperature, obtained from 5 different studies

Core Temperature	*Red Zone*			*Total*
	Safe	Warning	Critical	
Safe (< 38.5 °C)	13 (59.1%)	5 (22.7%)	4 (18.2%)	22 (100.0%)
Critical (> 38.5 °C)	5 (23.8%)	4 (19.1%)	12 (57.1%)	21 (100.0%)
Total	18 (41.9%)	9 (20.9%)	16 (37.2%)	43 (100.0%)

CONCLUSIONS

The RZ is an encouraging approach to warn occupational workers that they are approaching or/under excessive thermal physiological strain. This preliminary study suggests that there was a 60% – 80% probability that T_{core} is above 38.5°C when T_{skin} and HR of individuals fell into RZ classifications of "experiencing heat or critical conditions." Some of the RZ false positive results

might be related to heat acclimation state because heat tolerant individuals may be able to maintain lower T_{skin} in compensable environments than heat intolerant individuals despite their high T_{core}. The RZ function, derived from non-invasive T_{skin} and HR measurements, utilizing BMI is useful to warn of likely excessive T_{core} and thermoregulatory distress as it occurs. Further field measurements including various environmental, clothing, and operational conditions will be important to refine this warning method, increase confidence intervals, and improve applications to diversified military populations.

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